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The Superconducting Solenoid Magnets for MICE

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Introduction

The Muon Ionization Cooling Experiment (MICE) is a channel of superconducting solenoid magnets. The magnets in MICE are around the RF cavities, absorbers (liquid or solid) and the primary particle detectors [1], [2]. The MICE superconducting solenoid system consists of eighteen coils that are grouped in three types of magnet assemblies. The cooling channel consists of two complete cell of an SFOFO cooling channel. Each cell consists of a focusing coil pair around an absorber and a coupling coil around a RF cavity that re-accelerates the muons to their original momentum. At the ends of the experiment are uniform field solenoids for the particle detectors and a set of matching coils used to match the muon beam to the cooling cells. Three absorbers are used instead of two in order to shield the detectors from dark currents generated by the RF cavities at high operating acceleration gradients. A layout of the full version of MICE is shown in Figure 1 below.

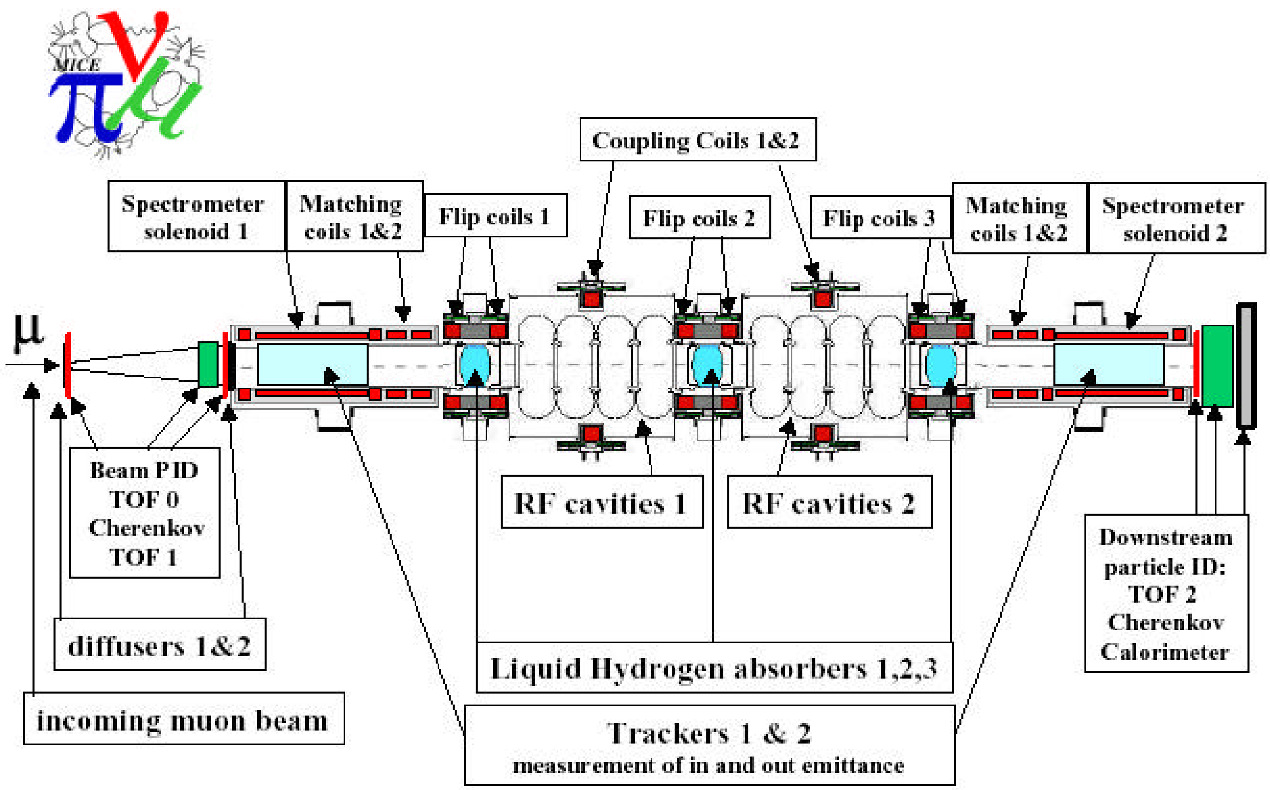

Figure 1. A General Layout of the Full MICE Experiment Showing all of the Superconducting Solenoids, the RF Cavities, the Liquid Hydrogen Absorbers, the Central Trackers in a Uniform Magnetic Field and Other Types of Detectors

The MICE superconducting solenoids will be fabricated in modular units. There are two reasons for wanting the solenoids in modular units. First, the superconducting solenoid magnets will be fabricated by three different groups in Europe and the United States. Second, there are several operating steps for MICE. Some of these operating steps are illustrated in Figure 2 below.

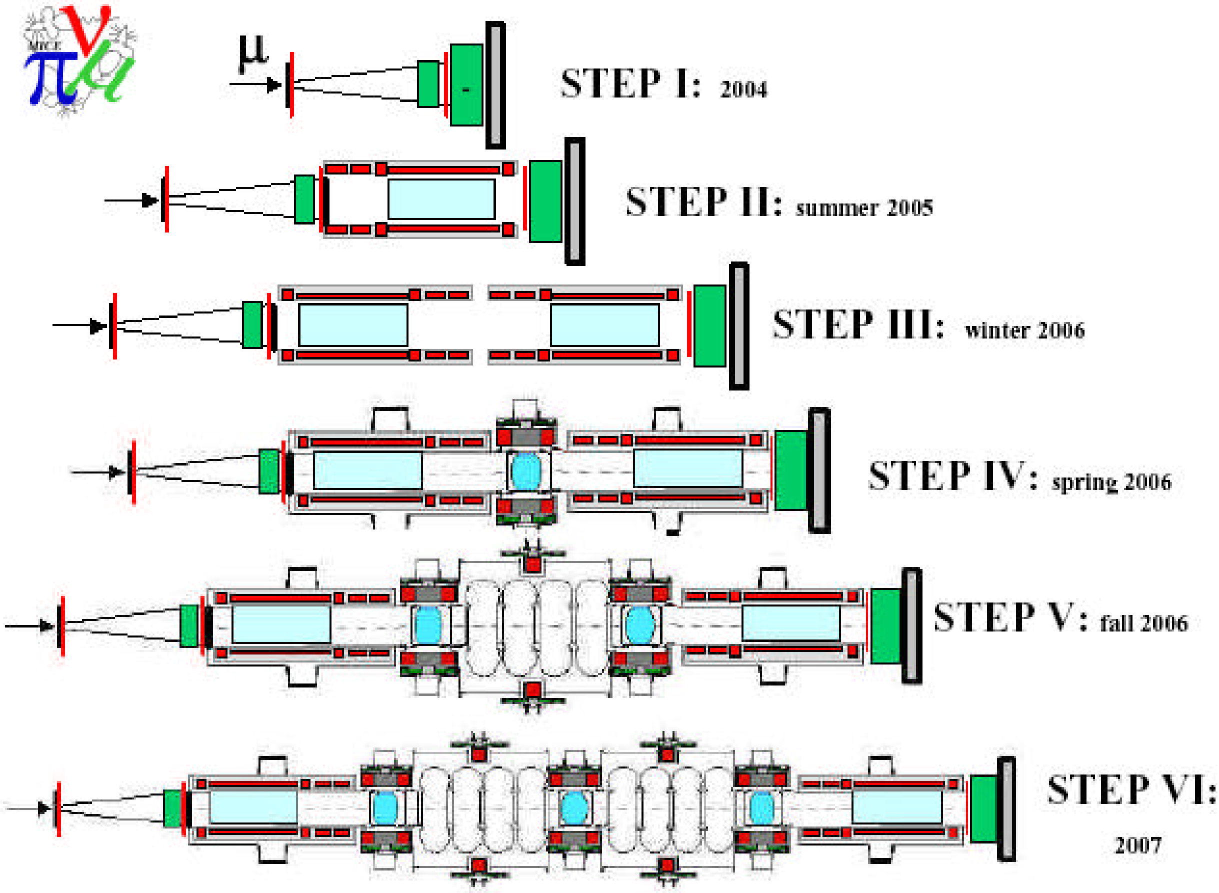

Figure 2. An Illustration of Six Operating Steps Proposed for MICE. These steps show the need for building the solenoids in modular units. Three types of solenoid units can be used to assemble the steps shown in this figure.

The three types of solenoids are illustrated in the six steps shown in Figure 2. No magnets are used in step I. One type of magnet is used in steps II and III. Two types of magnets are used in step IV. All three types of magnets are used in steps V and VI. The three types of magnets are 1) the short large diameter coupling solenoids around the RF cavities, 2) the focusing solenoid pair around the liquid hydrogen absorbers (or any other type of absorber), and 3) the detector uniform field solenoid and the matching coils needed to transfer the muon beam from the cooling channel to the detector solenoid without loss of the beam. The pair of matching coils in the detector magnet allows the acceptance of the detectors to be greater than or equal to the acceptance of the cooling channel.

Current thoughts call for the two detector solenoids (each is a five coil set on a common bobbin) to be built by an Italian group. The three focusing coil pairs (the two coils will be attached together cold) will be built by an English group and the two coupling coils will be built in the United States. This report presents a design for each of the three magnet types. The design presented in this report uses a MRI superconductor that is currently available in the United States from an American fabricator. The same conductor has been assumed for all the magnet types. It should be recognized that the three types of magnets would be built by three different groups. It is very unlikely that the same conductor would be used for all three magnet types given they will be built by groups in three different countries. However, a similar type of conductor probably will be used for the three magnet types.

The operating steps shown in Figure 2 assume that the focusing coil pair operates in the gradient mode (where the magnetic field on axis flips from one polarity to the other), but this does not have to be the case. It is possible for the focusing solenoids around the liquid hydrogen absorber to operate in the solenoid mode with a relatively uniform magnetic field on the solenoid axis. Since the solenoid operating (no field flip) mode for the focusing solenoids can not be precluded, the possibility of operating in both modes must be considered in the focusing solenoid design.

The ultimate design for the solenoids in the cooling channel is dictated by the average muon momentum and muon beam beta in the ionization cooling absorbers in the experiment [1]. The experiment should operate over a range of average momenta and beta in the absorber. MICE is designed with liquid hydrogen as the absorber material of choice. If one uses a solid absorber material, such as lithium hydride, the beta in the absorber region must go down in order to get the same overall cooling performance. Muon average momentum and beam beta in the focusing region of the absorber dictates magnet coil current density and the peak magnetic field in the coil for both the coupling and the focusing solenoids. Since the magnetic field in the uniform field region of the detector magnet is 4 T or lower, the current density in the five detector magnet coils and coil peak field in these coils are far less affected by changes in the average muon momentum and the beam beta in the absorbers. Table 1 below outlines the parameter space for the experiment one would want to do using the full MICE channel shown in Step VI of Figure 2 (the same case as Figure1).

Table 1. Focus and Coupling Coil Current Densities for Various Experiment Average Momentum and Betas in the Absorbers

Case	Average P (MeV/c)	Beta (mm)	Δp/p (%)	Focus J (A mm^{-2})	Coupling J (A mm^{-2})
1A	200	420	25	107	105
1B	240	420	25	128	126
1C	270	420	25	144	142
1D	300	420	25	161	158
2	200	260	20	126	93
3	200	160	17	140	67
4	200	100	14	154	50
5	200	55	8.	177	0

The peak field in the winding is directly proportional to the current density in the coil. For the focusing coil Bp = 0.058 J. For the coupling coil Bp = 0.051 J. J is coil current density (A mm^{-2}); Bp is peak field (T).

From a practical standpoint, the properties of a usable niobium titanium superconductor do not permit one to operate the standard MICE cooling channel for all of the cases shown above. For a typical

MRI conductor, the practical limit for the focusing coil current density is about 130 A mm^{-2} at a peak field in the winding of 7.6 T at 4.4 K. For the coupling coil, this practical coil current density limit is somewhat higher at say J = 158 A mm^{-2} at a field of 7.4 T in the conductor at 4.4 K. When one applies the practical current density limits to the coupling coils one sees that the current density for case 1D is not possible unless one drops the temperature in the superconductor. When one applies the practical current density limits to the focusing coils one can see that cases 1C, 1D, 3, 4, and 5 are not possible unless one drops the temperature of the superconductor. Cases 3, 4, and 5 do become possible if one is willing to reduce the average muon momentum. For case 3 the average momentum should be reduced to 180 MeV/c; for case 4 the average momentum should be reduced to 163 MeV/c; and for case 5 the average momentum should be reduced to 142 MeV/c. From a practical standpoint, one can operate MICE cases 1A, 1B, and 2 without reducing the superconductor temperature. Cases 3, 4, and 5 can operate with the niobium titanium MRI superconductor at 4.4 K at reduced average momentum.

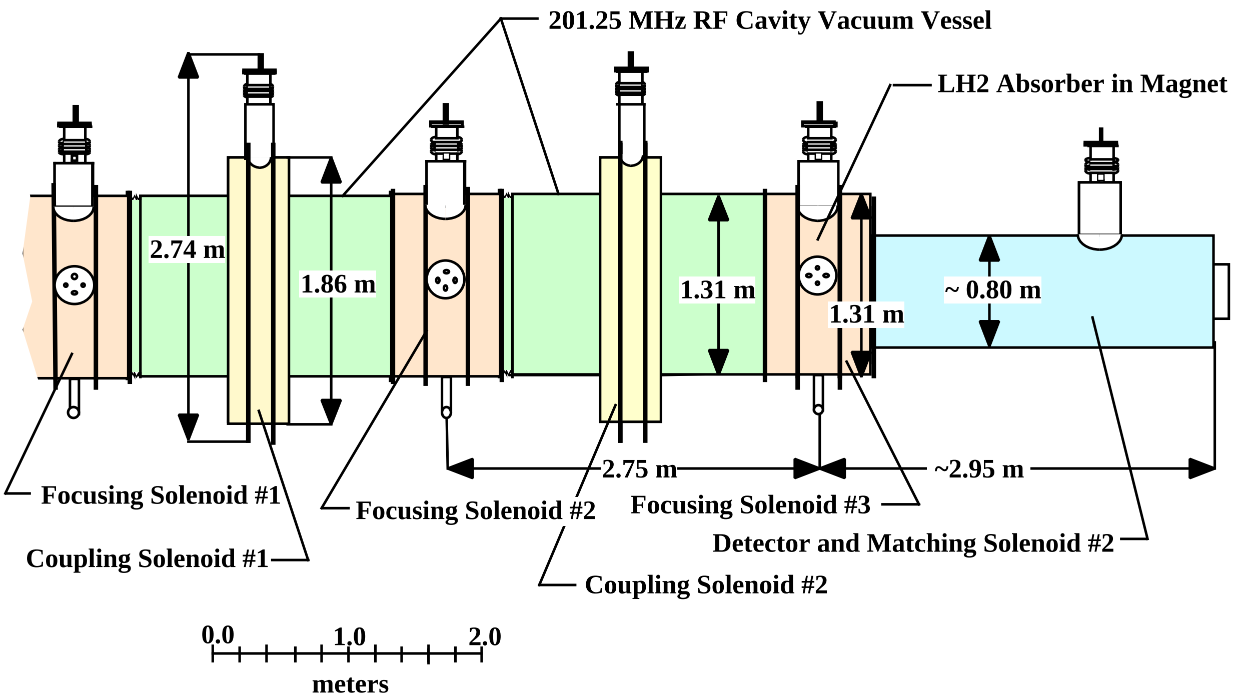

Figure 3. A Schematic Representation of the Outside of the MICE Magnet Cryostat. Note the tracker detectors, the RF cavities and the liquid absorber assemblies are covered by the magnet cryostats and the RF cavity vacuum vessels. The outside dimensions for the cryostats shown in this figure are approximate.

Figure 3 shows an outside view of the MICE magnet cryostats and the vacuum vessels that go around the MICE 201.25 MHz RF cavities. The assembly shown above applies to magnets that are cooled using two-phase helium in pipes that are attached to the superconducting coil support structure. As a result, the gas cooled leads for the focusing coils come from the magnet to the side. Forced two-phase helium cooling permits one to reduce the physical size of the cryostat, because there is no helium tank that is a part of the helium cryostat assembly. The cryostats for the focusing solenoids around the liquid hydrogen absorbers may have to be modified in order to meet RAL hydrogen safety standards.

Forced Two-phase Helium Cooling for the Solenoid Magnets

It is proposed that all of the superconducting coils for the MICE magnets are cooled by conduction from the magnet coil support structure or tubes attached directly to the coils. Most of the large detector magnets currently in service are cooled using two-phase helium in tubes attached to the coil support structure [3], [4]. For MICE, the magnet support structure will be cooled by two-phase helium in cooling tubes that have an inside diameter about 10 mm.

It is proposed that the MICE solenoid magnets will be cooled in series using a single cooling circuit that goes from the refrigerator through the magnets and back to the refrigerator. The volume of liquid helium in the solenoids will be very low (of the order of a few liters) as a result of it all being in 10 mm diameter tubes. The advantages of two-phase helium cooling of the magnets are as follows: 1) The cool down of the magnet string is straightforward and well controlled. 2) The overall mass of a tubular cooled magnet and its cryostat is less than the mass of a magnet cooled with helium bath cooling. This is an important factor for reducing the cost of the magnets. 3) The amount of helium in contact with the magnet coil during a quench is limited to the amount of helium in the cooling tube. Safety is much less of a problem compared to helium bath cooled magnets. Tubes always have a higher pressure rating than a cryostat helium vessel, and tubes are not covered by the pressure vessel code. 4) Helium services to the superconducting magnets can come into the cryostat from any direction, and the gas cooled electrical leads can be operated at any orientation including having the cold end up and the warm end down.

The downside of cooling with forced two-phase cooling is that the average coil temperature is increased. Depending on the design of the two-phase flow circuit and the refrigerator it is attached to, the coil operating temperature is increased from 0.1 to 0.2 K. A design operating temperature is between 4.4 K and 4.5 K. This may affect the design of the coil superconductor.

A Superconductor that can be used for All MICE Coils

For this report on superconducting solenoids for MICE, the same superconductor has been proposed for all three-magnet types. The proposed conductor is the same superconductor used to fabricate the Lab G solenoid at Fermilab [5]. This conductor is a standard MRI conductor that was made by IGC (now owned by Outokumpu). This conductor has the following characteristics: 1) The insulated are 1.0 by 1.65 mm with rounded corners. The insulation is 0.025 mm thick. 2) The copper to superconductor ratio is four. 3) The copper minimum residual resistance ratio is seventy-five. 4) There are 55 filaments of niobium titanium that are 78 μm in diameter. 5) The conductor twist pitch is 12.7 mm. 6) The guaranteed critical current for the conductor is 760 A at 5.0 T and 4.22 K. The conductor J_c is about 2960 A mm^{-2} at 5 T and 4.22 K. This is good quality MRI conductor.

A Coil Design for the MICE Cooling Channel Solenoid Coils

The two cell MICE cooling channel consists of two magnet types. There are three focusing solenoid pairs in three cryostats that contain both the focusing magnet and the liquid hydrogen absorber. There are two coupling solenoids that go around the two 201.25 MHz RF cavities. Two of RF cavity vacuum vessel sections connect the coupling coil cryostat to the focusing coil cryostats on either side of the RF cavity (see Figure 3). Figure 4 shows the relationship of the coupling coil to the focusing coils in one of the two MICE muon-cooling cells. Forces between the coupling coil and the focusing coil pair is carried through the RF cavity vacuum vessel that is shown as bridging the gap between the coils. Forces between the two coils in the focusing coil pair is carried by cold coil support structure that is around the coil pair. The coil section shown in deep red is about 65 percent conductor and about 35 percent insulation. The 4.4 K helium-cooling tubes are not shown in Figure 4.

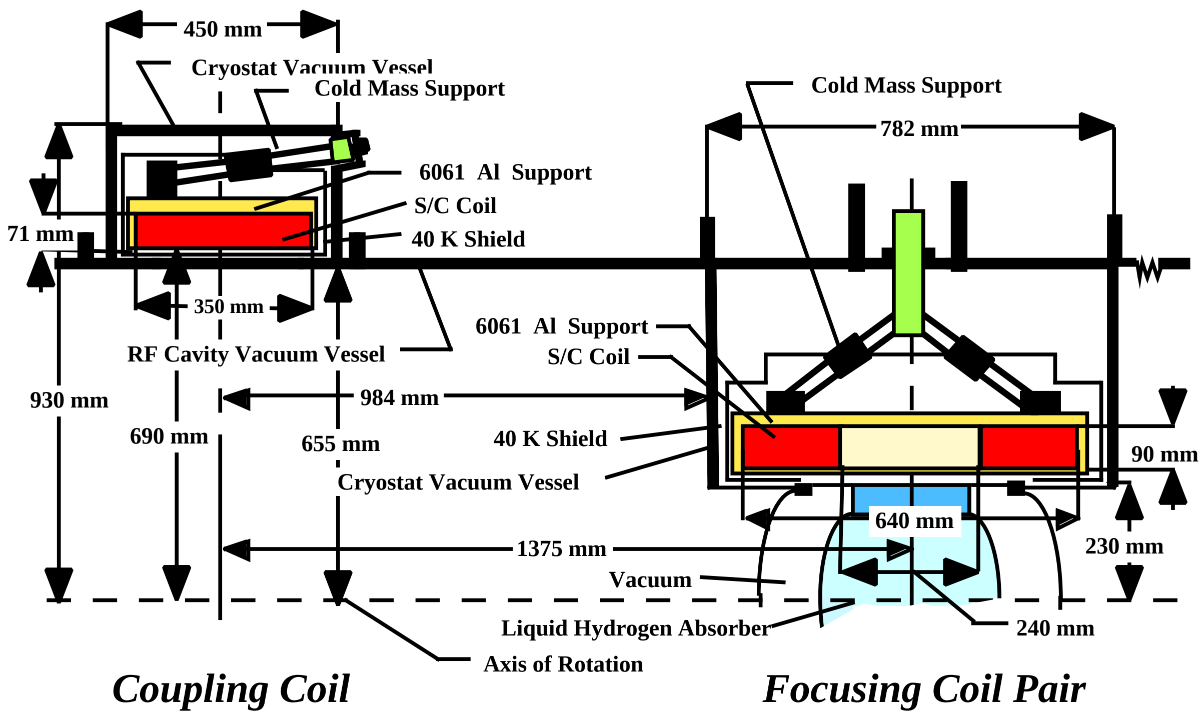

Figure 4. A Quarter Section of the MICE Muon Cooling Cell Showing a Coupling Coil and a Focusing Coil Pair
The 201.25 MHz RF cavity is not shown. The liquid hydrogen absorber is shown within the focusing coils.

Figure 5 is a cross-section of a single coupling coil that goes around the 201.25 MHz RF cavity. The proposed coupling coil cryostat has an inside diameter of 1310 mm. The cryostat outside diameter is about 1860 mm. The coil itself is 350 mm long and 71 mm thick. The coupling coil can be made somewhat shorter and thicker without affecting performance of the magnet are without increasing the peak filed in the magnet winding very much

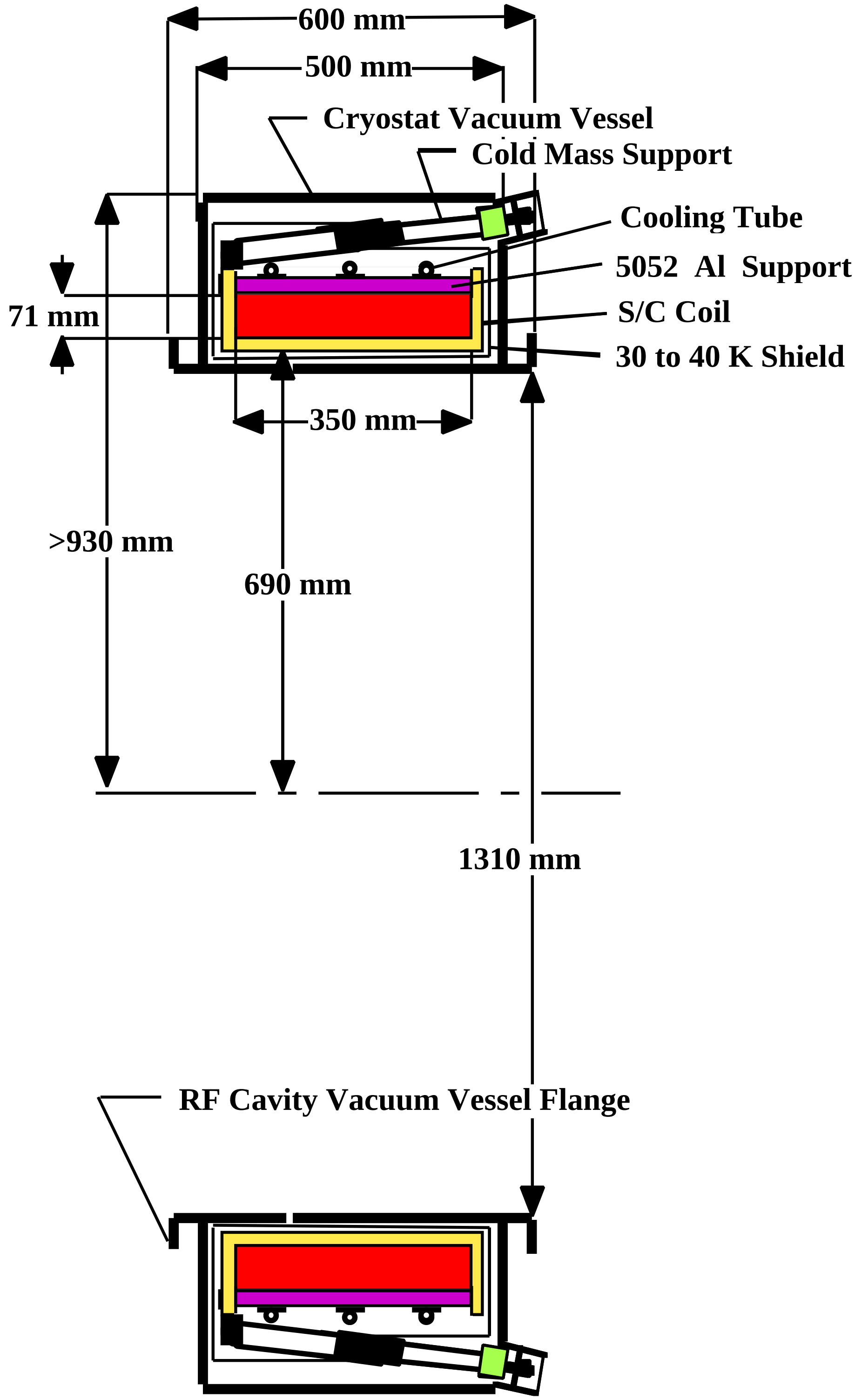

Figure 5. A Cross-section View of the Coupling coils for MICE. Note the coil section is slightly different from the one illustrated in Figure 4. In this case, the coil is would around an aluminum bobbin. The coil is then wrapped with a hard aluminum support structure to minimize the coil strain when it is powered. Figure 4 shows a coil shrunk fit into an aluminum support shell. The choice of fabrication technique is cost dependant. Either method will work.

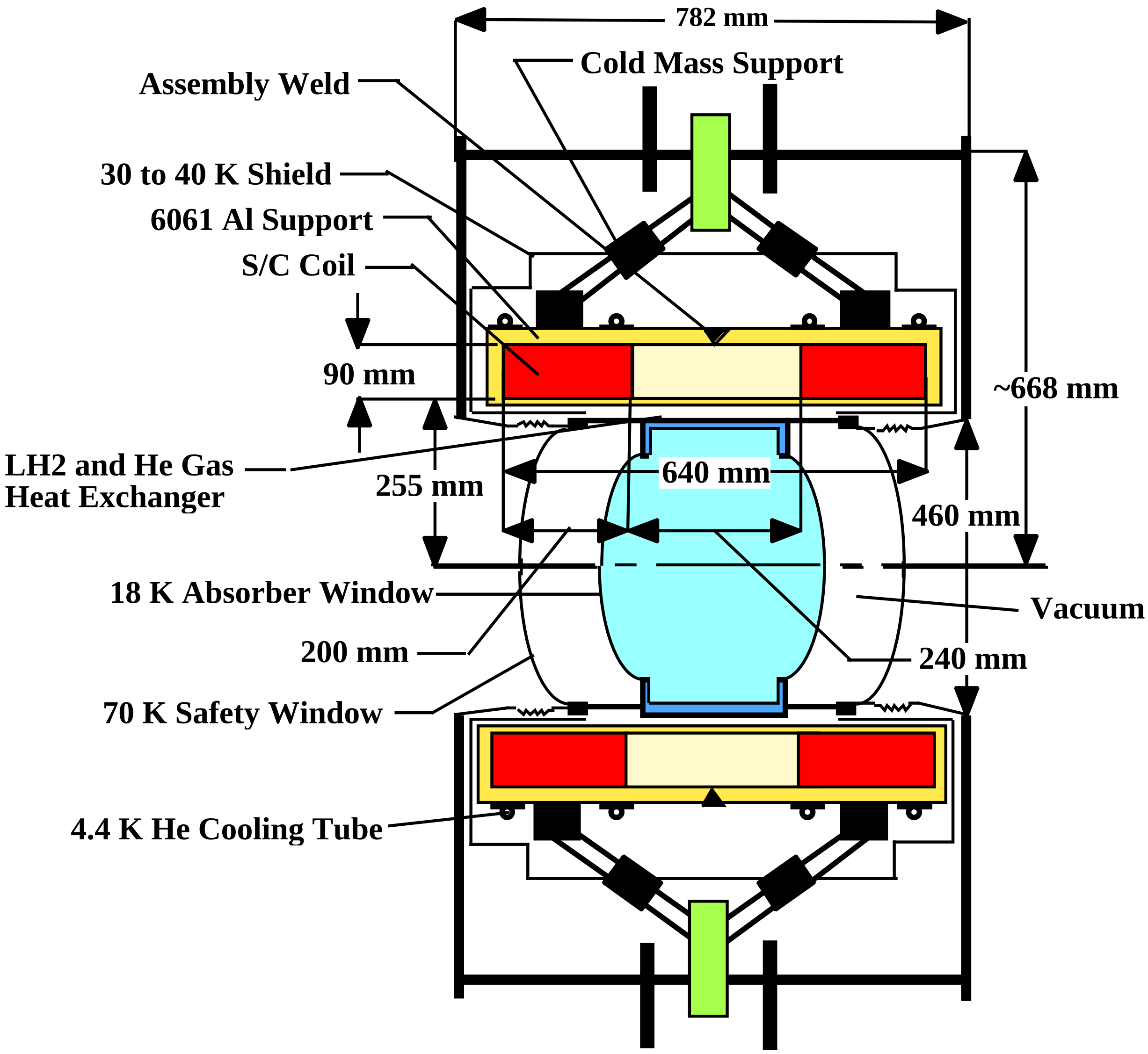

Figure 6. A Schematic Cross-section of the Focusing Coil Pair Integrated with the Liquid hydrogen Absorber. The approach shown assumes that the two coils will be assembled around the liquid hydrogen absorber and then welded together. When the focusing solenoid pair operate in its normal design mode (the gradient mode where the two coils operate at opposite polarity) a force up to 2.62 MN (267 metric tons) will be pushing the coils apart. This force must be carried by the hard aluminum support structure that is around the focusing coils. When the focusing coil operate in the solenoid mode (with the two coils at the same polarity), there will be a small force pushing the two coils together.

Figure 6 shows a cross-section of the focusing coil pair integrated with a liquid hydrogen absorber. The integration scheme shown assumes that the coils will be welded together around the absorber piping, which is not shown in Figure 6. The members that hold the coils together must carry large magnetic forces (up to 2.62 MN) when the MICE channel is running at 240 MeV/c. Figures 7, 8, and 9 show other views of how the liquid hydrogen (helium) absorber may be integrated into the focusing coils. Also shown in Figures 7, 8, and 9 are members that keep the focusing coils apart, when the focusing coil system is operated in the solenoid mode, with both coils at the same polarity.

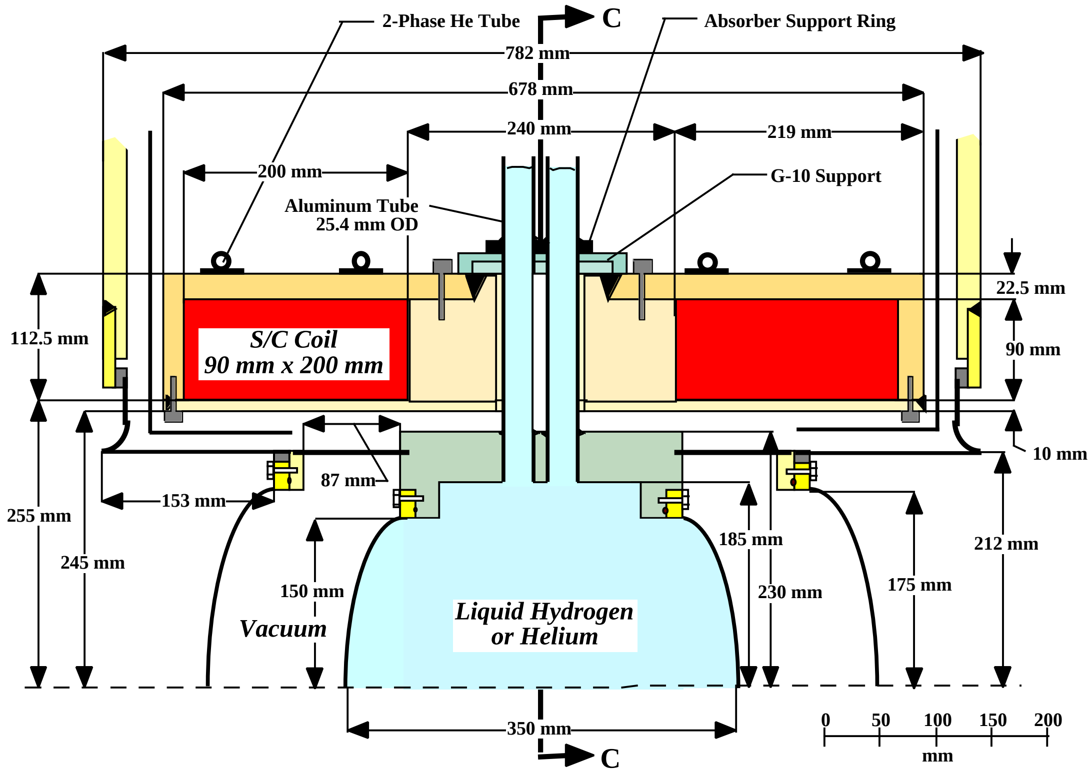

Figure 7. Cross-section A-A Showing the Focusing Coils and the Absorber through the Absorber Neck Region

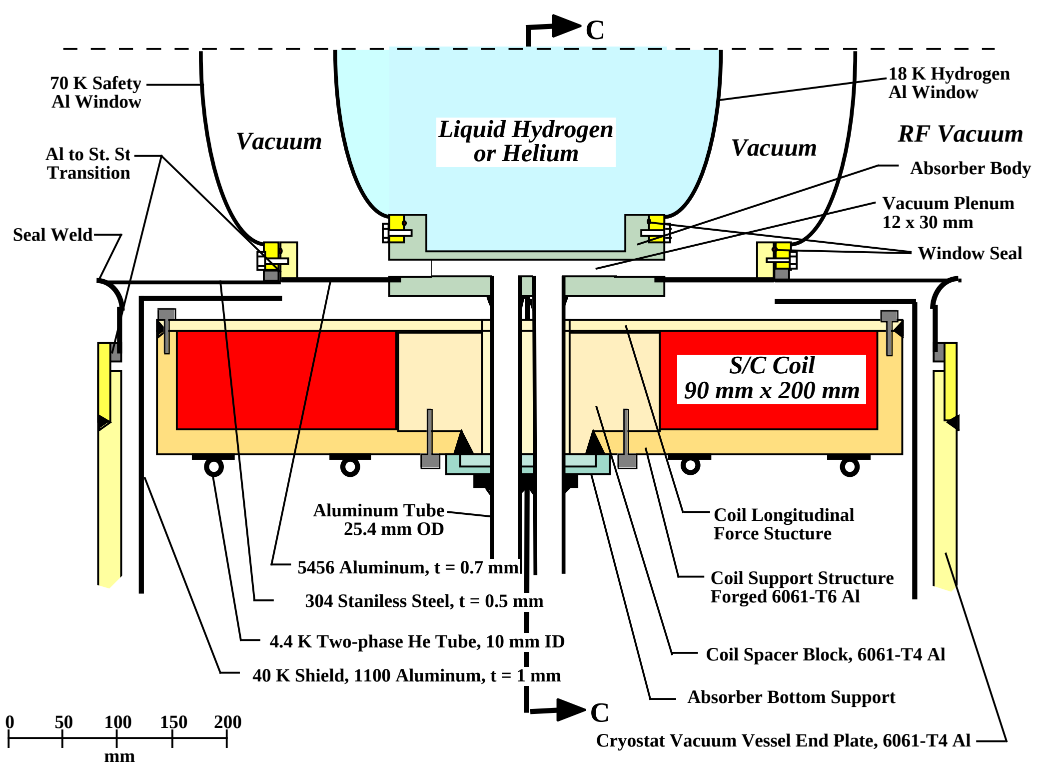

Figure 8. Absorber and Coil Cross-section Showing the Lower Part of the Absorber and the between Window Vacuum Pipes

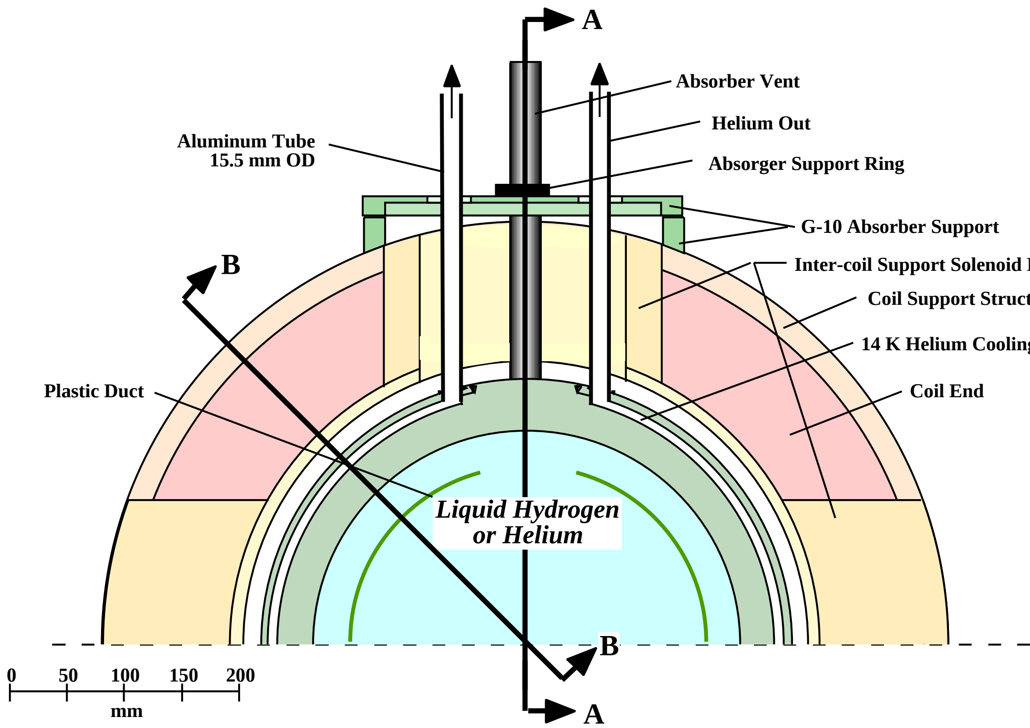

Figure 9. Cross-section C-C Showing the Upper Part of the Hydrogen Absorber installed in the Focusing Solenoid System

Superconductor Temperature Margin for the Cooling Cell Solenoid Coils

The focusing coil and coupling coil load lines are shown for the high field point in each magnet in Figure 10. In addition to the magnet load lines, there are the critical current versus magnetic induction lines for the MRI superconductor selected for the magnets. The conductor critical current is given at three temperatures 3.4 K, 4.2 K, and 5.0 K. An approximate line for 4.4 K is also given. In Figure 10, one can see that there is plenty of temperature margin for both the focusing and the coupling coils when the design cooling-channel operates at an average momentum of 200 MeV/c. The temperature margin for the focusing coil along the load line is about 1.1 K at this momentum. The temperature margin along the load line for the coupling coil is about 1.6 K at this momentum. Increasing the average momentum to 240 MeV/c means that the current in the coils must be increased 20 percent and the peak field in the conductor is also increased 20 percent. The focusing coil temperature margin is reduced to 0.3 K when MICE operates at a 240 MeV/c average momentum. The coupling coil temperature margin is reduced to 0.8 K at this average momentum. Experience with the Lab-G solenoid at Fermilab suggests that the MICE focusing coils should be able to operate with temperature margins below as 0.2 K along the load line, provided the there are no power surges and the cooling does not change [5], [6]. (The Lab-G solenoid is the same diameter as the focusing coils and it uses the same conductor that is proposed here.) From Figure 10, it is clear that there is a limit to the extent that one can push the magnets in MICE. Based on Figure 10, it should be possible to operate MICE with focusing coil currents up to 285 A. The coupling coil should not be pushed over this current either because its stored energy is larger.

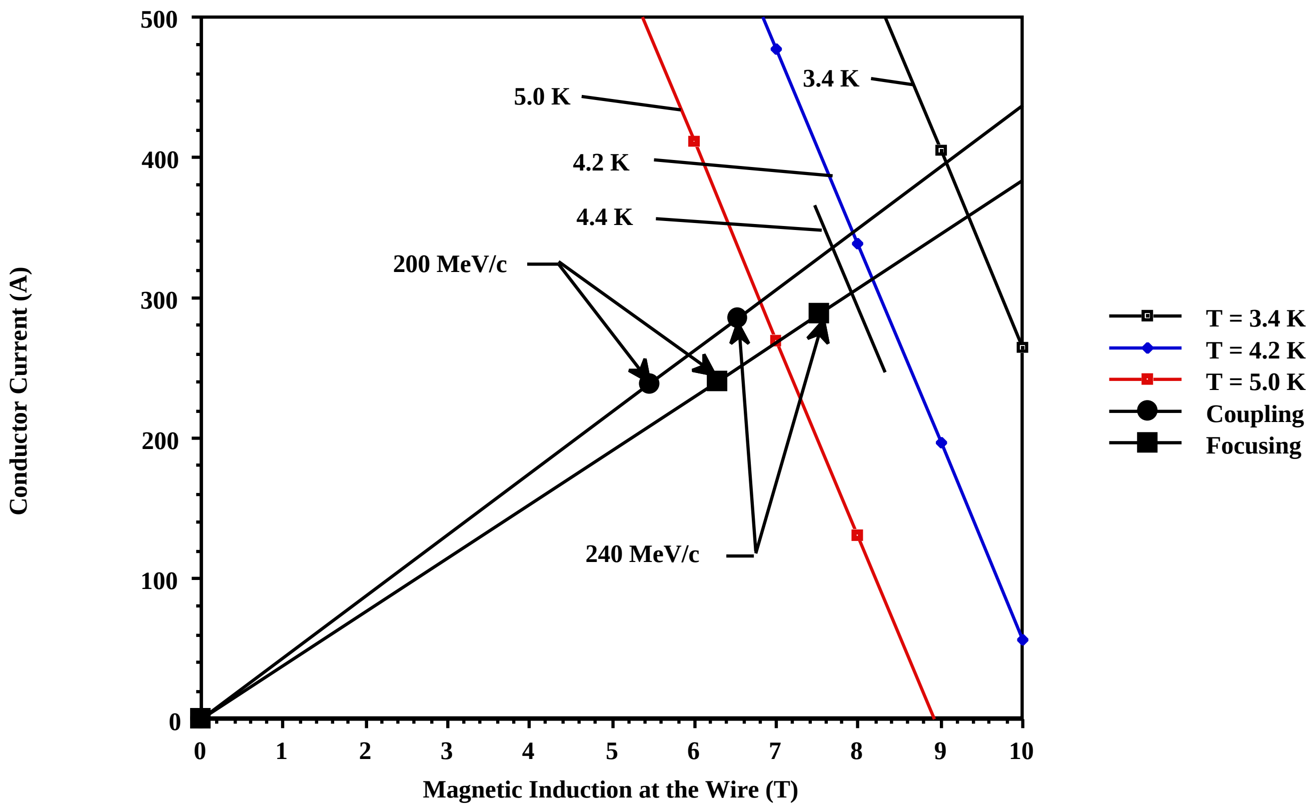

Figure 10. The Focusing Coil and Coupling Coil load Lines at the Peak Field Point in the Coil and the Conductor Critical Current Versus Magnetic Induction and Temperature

Forces on the Cooling Cell Solenoid Coils

The focusing coils see the highest coil forces. During normal operation of the cooling channel, the focusing coils operate in the gradient mode, which means that the two coil operate at opposite polarity. The focusing coil forces act to push the coils apart [2]. When the channel operates with an average momentum of 200 MeV/c, the force pushing the coils apart will be about 1.82 MN (186 metric tons). Since the channel may operate with an average momentum of 240 MeV/c, the focusing coils should be designed to carry forces of 2.62 MN (267 metric tons) or more. Since the two focusing coils are tied together by the cold coil support structure, these forces do not have to be carried to room temperature by the cold mass support system. The cold support system for the focusing coil pair should be designed for longitudinal force of 3.00 MN (306 metric tons). This design longitudinal force is almost identical to that seen by the Lab-G solenoid. When the focusing solenoid pair operates in the solenoid mode, the longitudinal force between the coils is much lower and it acts to push the two coils together. The design condition for this force pushing the coils together should be about 1.00 MN (102 metric tons).

The forces on the focusing coil pair that have to be transmitted to room temperature through the cold mass supports depends on the location of the focusing coil pair and the distance between the focusing coil pair and the detector solenoid magnet system. For the case shown in Figure 1 (or step VI in Figure 2) the net longitudinal force on the center focusing coil pair is zero. The net longitudinal force on the focusing coils next to the matching and detector coils will vary depending on the experimental case (see Table 1) and the distance between the first matching coil and the nearest focusing coil. The net longitudinal force on the end focusing coil pairs is very sensitive to this coil spacing. A change is the longitudinal distance between the current centers of the outermost focusing coil and the first matching coil from 400 mm to 413.5 mm reduced the force carried by the cold mass supports from 608 kN to 187 kN. The net force change is about 421 kN for 13.5-mm change in coil spacing between the end focusing coil and the first matching coil. It is interesting to note that the net force on the detector and matching coil set was also reduced by about 427 kN by moving the end focusing coils away from the matching coil by the same 13.5 mm. It appears that even a small change in the spacing between the outer focus coil set and the first matching coil will have a large effect on the cold to warm force seen by both coil sets. This effect should be studied in a systematic way, so that one can lower the longitudinal forces.

It is clear that the cold mass support system for the focusing magnet should be capable of safely carrying a longitudinal force of at least 500 kN (50 metric tons). The exact design value for this longitudinal force requires additional study of all of the possible experimental cases and a number of different spacings between the focusing coil set ant the end of the detector and matching coil set. The net force on the focusing coils should also be studied for different magnet quench scenarios. The support system design requirement for the focusing coils dictate that support system be designed to carry a force of at least 100 kN (10 metric tons) in the transverse direction to allow for iron in the experimental hall. The cold to warm forces generated by the focusing coils must be carried from cryostat to cryostat through the RF cavity vacuum vessel or through connections to the experimental floor. The net force on the detector solenoid must be carried through a connection from its cryostat to the focusing coil cryostat or through connections to the experimental floor..

The net force on the coupling coils is about 84 kN case 1A for the full experiment. For case 1B where the average momentum is increased from 200 MeV/c to 240?meV/c, this force will increase to 121 kN. This relatively small force is affected very little by the same 13.5-mm change in current center to current center spacing. (The force on the coupling coils was reduced from 86 kN to 84 kN.) This means that the force on the coupling coils is not due to interaction with the focusing coil pair or the matching coils. The source of the net force on the coupling coils is probably due to the field flip that occurs from on cell to the next. If there is no field flip in the cells, the coupling coil net force will probably change in sign but not much in magnitude. It is clear that the coupling coil cold mass support system should be designed to carry at least 250 kN (25 metric tons) in any longitudinal direction. Most of the self-centering support system that have been studied will carry a longitudinal force of this magnitude. As with the focusing coils, the forces should be studied for all experimental cases and all of the fault cases that can be envisioned. As with the focusing coil support system, the coupling coil support system design requirements dictate that support system be designed to carry a force of at least 100 kN (10 metric tons) in the transverse direction to allow for iron in the hall. The cold to warm forces generated in the coupling coils must be carried to adjacent cryostats through the RF cavity vacuum vessel or through attachments to the experimental floor. It should be noted that the net longitudinal force for MICE is zero provided there is no iron in the hall to generate a net force. All of the cryostat support systems should be designed to allow for the presence of an iron in the experimental hall.

Magnet Parameter for the MICE Cooling Channel Magnets

The basic parameters for the focusing coils and the coupling coils are presented in Table 2. It is assumed that the focusing and coupling coils are wound with the MRI superconductor previously described in this report.

Table 2. Focusing and Coupling Cooling Channel Magnet Parameters

Parameter	Focusing Magnet	Coupling Magnet
Inner Cryostat Radius (mm)	230	655
Outer Cryostat Radius (mm)	668	930
Cryostat Length (mm)	782	500
Inner Coil Radius (mm)	255	690
Coil Thickness (mm)	90	71
Coil Length (mm)	200	360
Number of Coils in the Cryostat	2	1
Longitudinal Distance between Coils (mm)	240	-NA-
Number of layers per Coil**	66	52
Number of turns per Coil Layer**	121	218
Magnet Design Current (A)*	240.3	238.2
Coil Average J (A mm^{-2})*	106.7	105.6
Magnet Self Inductance (H)*	~45	~230
Stored Energy at Design Current (MJ)*	~1.3	~6.5
Peak Field in the Coil at Design Current (T)*	6.27	5.45
Design Temperature Margin at Design Current* (K)	~1.1	~1.6
Cold Inter-coil Force at Design Current (MN)*	1.82	-NA-
Design Warm to Cold Longitudinal Force (MN)	0.50	0.20

* For the standard channel Stage VI, Case 1A with p = 200 MeV/c and β = 42 cm

** For insulated conductor dimensions of 1.65 x 1.00 mm and a layer thickness of 1.35 mm

Cooling Channel Solenoid Power Supplies and Quench Protection

It is proposed that all the focusing solenoids be hooked in series and that they be powered by a single 300 A, 10 V power supply. Each focusing coil cryostat will have a pair of leads for each of the two coils. This permits one to change the polarity of one coil in the pair with respect to the other. Since the coils have a support structure that is in direct thermal contact with the superconducting coils, the primary mode of quench protection can be through quench back [3],[6],[7]. As the field decays during a quench, a current is induced in the support structure. The current in the support structure caused IR heating in the support structure, which in turn warms up the superconducting coils. If one focusing coil quenches the other focusing coils will quench through quench back from the support structure.

It is proposed that both coupling coils be powered from a single 300 A, 10 V power supply. Even though the stored energy of the coupling coils is large, these coils can also be protected through quench back from the coil support structure. As with the focusing coils, a quench in one of the coupling coils will cause the other coil to quench. Quench back in the coupling coils can be improved by winding two layers of pure RRR = 300 into the center of the coupling coil. The ends of two layer copper coil should be together to form a closed circuit. The problem with using a shorted copper coil within the coupling coil is that it will require that the coupling coils not be charged to quickly. Since the MICE coils are essentially DC coils, this is not a large penalty to pay to improve the quench back characteristics of the coupling solenoids.

Possible Variations of Focusing and Coupling Coil Designs

Besides changing the conductor size and thus the coil design current, some changes could be made in the coil design as compared to the design given in the previous sections of this report.

An example of such changes is reducing the copper to superconductor ratio in the conductor for the focusing coil. A reduction of the copper to superconductor ratio (so there is more superconductor in the conductor) in the focusing coil could increase the temperature margin for this coil. Reducing the copper to superconductor ratio from four to three would increase the superconductor area in the conductor about 25 percent. If the J_c of the superconductor is not changed in the process of reducing the copper to superconductor ratio, the critical current for the conductor would increase about 25 percent at a given temperature and magnetic induction. The temperature margin for the 200 MeV/c case (Case 1A) would increase from 1.1 K to about 1.4 K. For the 240 MeV/c case (Case 2A) the temperature margin increases from 0.3 K to 0.5 K. Decreasing the copper to superconductor ratio further will increase the temperature margin more, but this increase in temperature margin will be at the price of conductor stability. Even when the conductor copper to superconductor ratio is reduced from four to three, stability is an issue. A conductor which has a copper to superconductor ratio of three should have a copper RRR greater than 200.

The copper to superconductor ratio for the coupling coil can be increase. This reduces temperature margin, but it increases conductor stability and increases the current squared integral with time for safe quenching, particularly if the copper RRR is increased along with the copper to superconductor ratio. Increasing the copper to superconductor ratio from four to six will reduce the conductor temperature margin at 200 MeV/c (Case 1A) from 1.6 K to about 1.2 K. At 240 MeV/c (Case 2A) the temperature margin is reduced from 0.8 K to 0.35 K by increasing the copper to superconductor ratio from four to six. The best way to increase the temperature margin of the coupling coil while increasing the copper to superconductor ration is to increase the number of layer in the coil.

A Coil Design for the Matching and Detector Solenoid Coil Set

It has been proposed the detector solenoid, which generates a uniform field for the trackers, be combined with one or more solenoid that match the field from the focusing solenoid to the detector solenoids. One can achieve a uniform magnetic field (uniform to at 3 parts in 1000) over a length of 1000 mm and a diameter of 300 mm by using a three coil set that has a total length of about 1700 mm. A five coil set that is 1700 mm long can generate a field uniformity that is better than 5 parts in 10000 over the same length and diameter. A careful sixth order coil design may permit one to shorten the length of the coil set needed to produce a uniform field over the desired length and diameter. This has not been investigated. A minimum set of two matching coils is needed to match the muon beam from the focusing coils and absorber to the uniform field section. Figure 11 shows the field on axis for the 200 MeV/c MICE channel from the center the channel to its ends. Since there is a field flip at the center of the standard MICE channel, B(-x) = -B(x). One can see from Figure 11 that the transition from the focusing (field flip) region to the uniform field region is smooth. As a result very few muons are lost in the transition from the cooling channel to the detector or from the detector to the cooling channel.

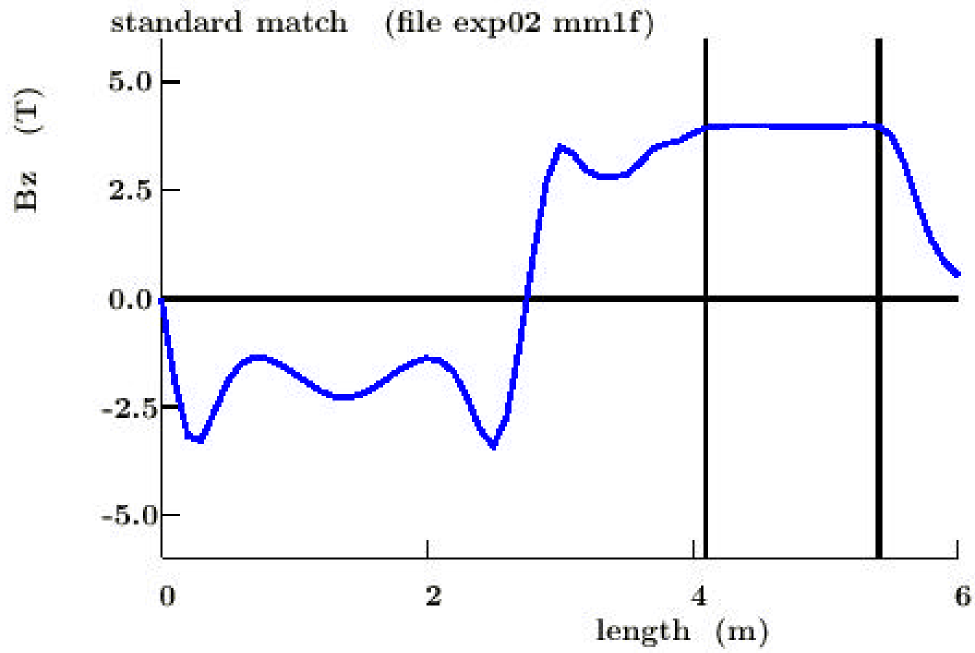

Figure 11. The Magnetic Induction on the Axis of the MICE Channel as a Function of Distance Z for the MICE Base Line Case (Case 1A) for z greater than 0. Note: the field flips at z = 0 and z = ± 2.75 m, and B(-z) = -B(z).

Bob Palmer analysis shows that the field in the good field region where the detector is located is good to about 3 part in 1000. This analysis has been verified by calculations at the Rutherford Appleton Laboratory using OPERA3D (TOSCA). The field uniformity is certainly better that one- percent in the detector region that is 1000 mm long and 300 mm in diameter. When Bob Palmer did the matching calculations he used matching coils that were 200 mm long with an inside diameter of 500 mm. These coils were spaced about 150 mm apart and about 120 mm from the end coil of the uniform filed section. Bob Palmer's original design called for the first matching coil to be about 200 mm from the nearest focusing coil. The design was modified without shifting Bob Palmer's original current centers so that matching coil thickness can be the same and so that their currents would be in the correct range around 210 A. The uniform field solenoid end coils were lengthened and their thickness was set at twice the thickness of the center coil for the uniform field solenoid. The three-coil uniform-field solenoid is designed to produce a uniform field when all three coils are powered to the same current.

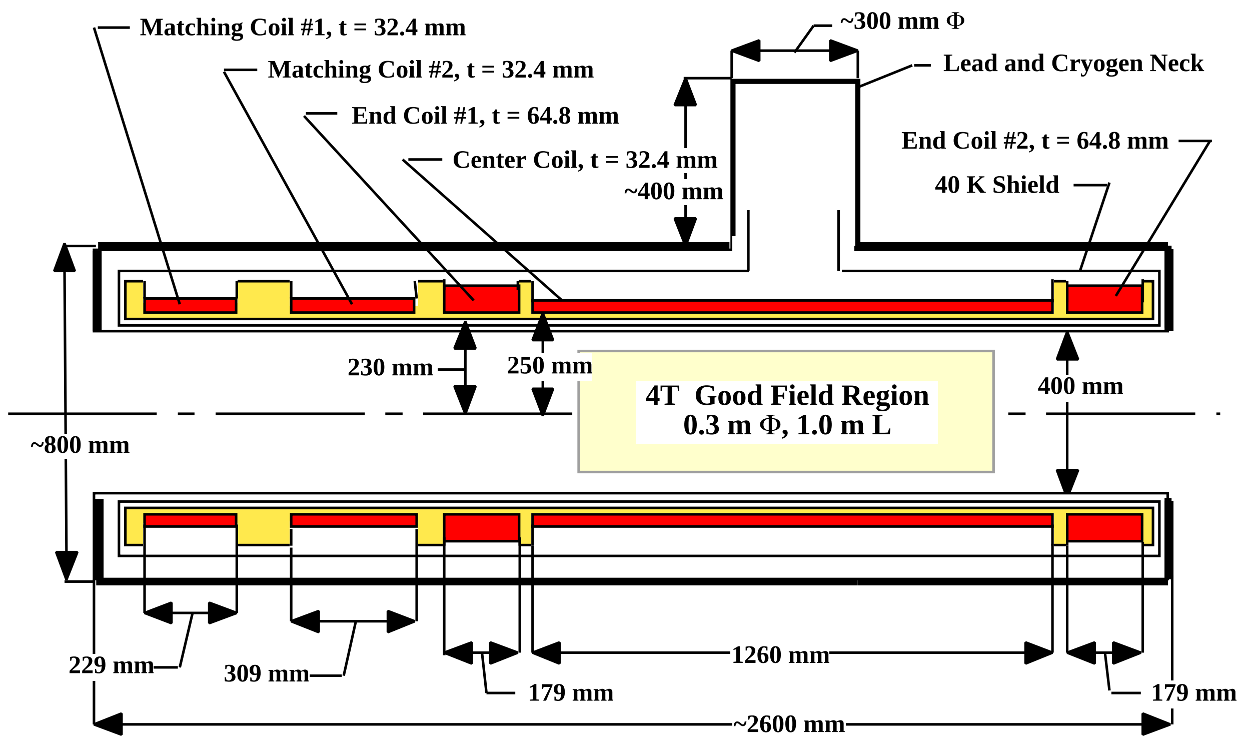

Figure 12. A Matching and Detector Solenoid Cross-section that uses the Conductor used for the Cooling Channel Magnets. The center coil for the detector solenoid and the end coil away from the matching solenoids can be powered with one power supply. The other three coils must be separately powered to match the cooling MICE cooling channel. The two-phase helium cooling tubes for the coils are not shown in this view.

Table 3. Matching and Detector Coil Parameters for a Magnet using the Same Conductor as the Cooling Channel Magnets

Parameter	Match #1	Match #2	End #1	Center	End #2
Inner Coil Radius (mm)	250	250	250	250	250
Coil Length (mm)	229	309	179	1260	179
Coil Thickness (mm)	32.4	32.4	64.8	32.4	64.8
Number of Layers**	24	24	48	24	48
Number of Turns per Layer**	128	192	112	788	112
Design Current (A)*	211.7	211.0	167.3	215.7	215.7
Overall Coil J (A mm^{-2})*	87.7	97.1	77.5	91.5	91.5
Self Inductance (H)	5.2	11.5	17.7	61.2	17.7
Stored Energy (MJ)*	0.12	0.26	0.25	1.43	0.42
Peak Field in the Coil (T)*	3.4	4.5	4.9	4.2	5.1
Temperature Margin (T)*	2.4	2.0	2.1	2.2	1.8

* for the standard experiment Stage VI (Fig. 2), Case 1A with p = 200 MeV/c and beta = 420 mm

** For insulated conductor dimensions of 1.65 x 1.00 mm and a layer thickness of 1.35 mm

Figure 12 shows a cross-section of a five coil matching and detector solenoid set that uses the same MRI conductor used for the focusing and coupling solenoids shown in Table 2. Table 3 presents the parameter of the coils shown in Figure 12. From Table 3, it is clear that the temperature margins for the matching and detector solenoid coils are large. It is clear that the current in these coils can be increased by 40 percent or more without having a temperature margin that is too small. This means that there is a lot of ability to tune the channel and match the detector to the cooling part of the channel. It appears that the tracking detectors could be operated at a central induction as high as 5.0 T and still be able to match the detector solenoid with the rest of the cooling channel. The values of inductance given in Table 3 are the inductance value for individual coils. Since these coils are well coupled to each other the inductance figures shown do not have much meaning.

The inter-coil forces in the longitudinal direction for the solenoid system shown in Figure 12 are quite high (about 1.35 MN (138 metric tons). The largest force is generated by the radial component of magnetic field that reacts with the current in the detector end coil that is away from the matching coils. This large force, which pushes the matching and detector coil set toward the focusing coil set at the end of the cooling channel, is partly offset by longitudinal forces in the other four coils. The coil bobbin carries these inter-coil forces. The forces for the most part will put the bobbin in compression. The net force that is seen by the cold mass support is a strong function of the distance between the matching and detector solenoid set and the adjacent focusing coil pair. These forces should be carefully studied for each stage of the experiment and each of the operating cases for the final channel and the intermediate step. The force studies should be made before the detector solenoids and their cryostats are fabricated. It seem reasonable that one design the matching and detector coil set for a longitudinal cold to warm force of 500 kN (50.1 metric tons) pushing toward the nearest focusing coil set. The cryostat cold mass support system can be designed for longitudinal forces in a direction away from the focusing coil set of 200 kN (20 metric tons). The support system should be designed for forces in the transverse direction of 100 to 150 kN (10 to 15 metric tons).

The Coil Currents for Various Cases of the Full Version of MICE

Table 1 shows the parameters for various experiments that one would like to do with the standard MICE cooling channel and detector arrangement that is shown in Figure 1 (also Stage VI in Figure 2). One can not do all of the experimental cases shown in Table 1. Due to limits of the current carrying capacity of the superconductor in the focusing coils and the coupling coils, one can not do cases 1C, 1D, 3, 4, or 5. The experiments represented by cases 3, 4, and 5 can be done if one is willing to reduce the average muon momentum for these cases. For case 3, the average momentum should be 180 MeV/c; case 4 should be 160 MeV/c; and case 5 should be 140 MeV/c. Table 4 shows the average momentum and beta for cases 1A, 1B, 2, 3, 4, and 5. For these same cases, the currents in the focusing coils, the coupling coils, the matching coils, and the three detector solenoid coils are presented in the table. From Table 4, on can see that MICE is capable of doing the muon cooling experiment over a wide range of average momenta and beta in the absorber. The beam low beta cases are particularly important if one wants to do ionization cooling with lithium hydride or lithium absorbers.

Table 4. The Average Momentum, Beta, and Coil Currents for the MICE Magnets operating over a Range of Conditions

Parameter	Case1A	Case 1B	Case 2	Case 3	Case 4	Case 5
Average p (MeV/c)	200	240	200	180	160	140
Absorber Beta (mm)	420	420	254	167	104	57
Δp/p (percent)	25	25	20	17	14	8
Spectrometer B (T)	4.0	4.0	4.0	3.6	3.2	2.8
Focusing #1 I(A)	-240.3	-288.4	-285.2	-284.1	-280.3	-278.5
Coupling I (A)	-238.2	-285.8	-209.0	-159.5	-105.5	-0.0
Focusing #2 I (A)	-240.3	-288.4	-285.2	-284.1	-280.3	-278.5
Focusing #3 I (A)	240.3	288.4	285.2	284.1	280.3	278.5
Matching #1 I (A)	211.7	242.8	217.4	177.9	142.1	67.8
Matching #2 I (A)	211.0	224.8	161.6	106.8	32.4	-40.9
End Coil #1 I (A)	167.3	163.8	174.6	165.9	159,9	153.6
Center Coil I (A)	215.7	215.7	215.7	194.1	172.6	151.0
End Coil #2 (A)	215.7	215.7	215.7	194.1	172.6	151.0

* The coils that shown are for positive x. I(-x) = - I(x).

Cases 1B, 2, 3, 4, and 5 drive the focusing coils to nearly their critical current at 4.4 K. The temperature margin for the focusing coils for these cases is about 0.3 K for an operating temperature of 4.4 K. The coupling coils are not pushed near their limit. None of the matching and detector coils are anywhere near their critical current limit. It appears that the cost of the matching and detector coils can be brought down by using less conductor in these coils.

Matching and Detector Solenoid Power Supplies and Quench Protection

It is proposed that the coils in the matching and detector solenoid set be separately powered except for two coils. Two coils that can share a common power supply are the center coil of the uniform field solenoid and the end coil of that solenoid that is farthest from the matching coils. The current in the other end coil must be different because it is part of the field matching system. If the detector at one end of the experiment is identical to the detector at the other end of the experiment, the coil in one matching and detector solenoid set can be in series with corresponding coil in the other matching detector solenoid set. For maximum flexibility, there should be four 300 A, 10 V power supplies for each matching and detector solenoid set. If the detector at both ends of the experiment are identical, the four 300 A, 10 V power supplies can be used for both matching and detector coil sets.

Since the coils have an aluminum bobbin that is in direct thermal contact with the superconducting coils, the primary mode of quench protection can be through quench back. The coils in the matching and detector solenoid set are coupled inductively to each other inductively. A quench in one coil in the set will probably cause a quench in all of the coils in the set. Since the matching coils are closely coupled inductively with the adjacent focusing coils. A quench in the match and detector solenoid quench will probably cause a quench in the focusing coils as well.

The Italian Design for the Matching and Detector Coil Solenoids

The group at INFN Genoa has proposed to build the matching and detector solenoids [9]. Their preliminary design is somewhat different than the design shown in Figure 12. The Italian design has a stainless steel bobbin instead of an aluminum bobbin. The helium cooling tubes must be attached directly to the coils, because the stainless steel bobbin is a poor conductor of heat compared to an aluminum bobbin. The Italian coil design uses the conductor stabilized with copper to conduct heat within their coils. The magnetic hoop forces are carried by the copper stabilizer within the coils. The Italian coils have an average current density that is about two thirds of that shown in Table 3. The reasons for this are a lower current density superconductor, and a higher copper to superconductor ratio conductor. The Italian coil design current is about 20 percent higher than the design current shown in Table 3. Like the design shown in Table 3, these coils can be powered with four 300 A, 10 V power supplies.

The superconductor proposed for the Italian matching and detector solenoids is an LMI conductor designed for MRI magnets. This conductor has the following parameters: 1) The insulated dimensions of the conductor are 1.65 mm by 2.40 mm. The corners are rounded to prevent the insulation from cracking. 2) The copper to superconductor ratio is six. 3) The copper has a RRR of 75. 4) Each conductor consists of 92 filaments that are 80 μm in diameter. 5) The conductor is twisted. 6) The design critical current is 950 A at 4.2 K and 5.0 T. The critical current versus induction and temperature is similar to the conductor used for the focusing and coupling magnets.

Table 5 shows the basic parameters of the Italian matching and detector solenoid coil set. The magnets in Table 5 have similar stored energy to the magnets is Table 3. A section of the Italian matching and detector magnet and its cryostat is shown in Figure 13. Table 6 shows the current for the magnets in MICE when the Italian matching and detector solenoid is used in place of the magnet that uses the 1.00-mm by 1.65-mm superconductor.

Table 5. The Design Parameters for the Italian Matching and Detector Magnet

Parameter	Match #1	Match #2	End #1	Center	End #2
Inner Coil Radius (mm)	255	255	250	250	250
Coil Length (mm)	202	202	120	1260	120
Coil Thickness (mm)	50	73	116	50	149
Number of Layers**	30	44	70	30	90
Number of Turns per Layer**	84	84	50	525	50
Design Current (A)*	254.1	267.8	257.0	258.9	257.9
Overall Coil J (A mm^{-2})*	63.4	67.1	64.6	64.7	64.9
Self Inductance (H)	5.8	8.8	8.9	46.2	14.9
Stored Energy (MJ)*	0.13	0.32	0.29	1.55	0.50
Peak Field in the Coil (T)*	3.4	4.4	4.9	4.2	5.0
Temperature Margin (T)*	>2.5	>2.0	1.8	>2.0	1.8

* for the standard experiment Stage VI (Fig. 2), Case 1A with p = 200 MeV/c and beta = 420 mm

** For insulated conductor dimensions of 2.40 x 1.65 mm and a layer thickness of 1.66 mm

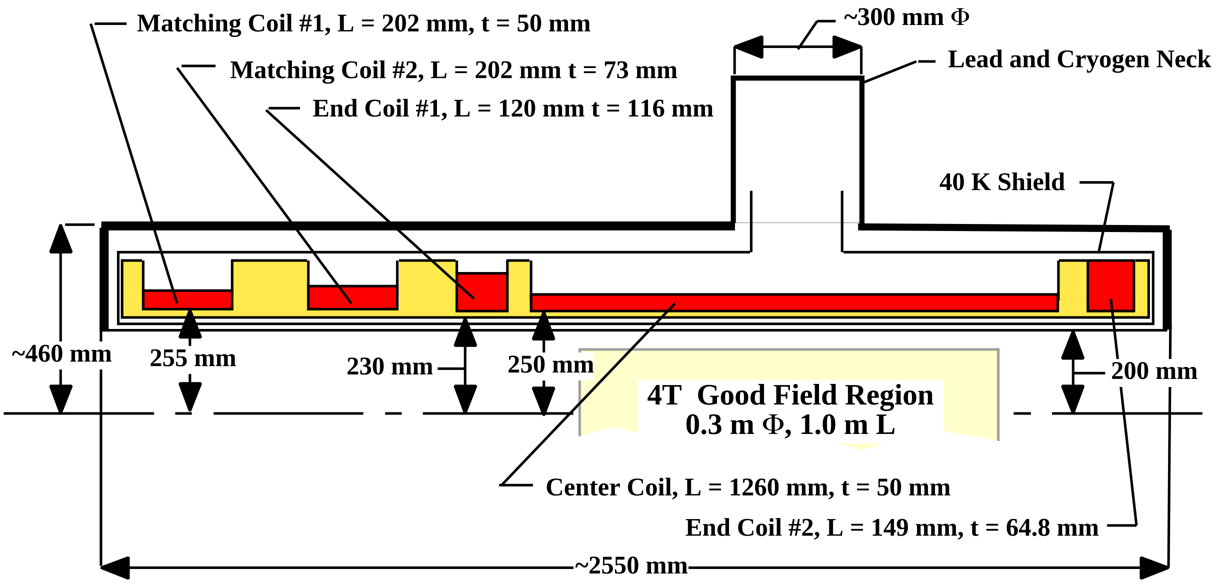

Figure 13. A Cross-section View of the Upper Half of the Italian Design Matching and Detector Magnet for MICE
The coils in the Italian design are thicker because the superconductor is larger. The coils are designed to carry the same current. The tubes for cooling the coils are not shown in this view.

Table 6. The Average Momentum, Beta, and Coil Currents for the MICE Magnets operating over a Range of Conditions
The matching and detector coils are the Italian design. This table should be compared to Table 4.

Parameter	Case1A	Case 1B	Case 2	Case 3	Case 4	Case 5
Average p (MeV/c)	200	240	200	180	160	140
Absorber Beta (mm)	420	420	254	167	104	57
Δp/p (percent)	25	25	20	17	14	8
Spectrometer B (T)	4.0	4.0	4.0	3.6	3.2	2.8
Focusing #1 I(A)	-240.3	-288.4	-285.2	-284.1	-280.3	-278.5
Coupling I (A)	-238.2	-285.8	-209.0	-159.5	-105.5	-0.0
Focusing #2 I (A)	-240.3	-288.4	-285.2	-284.1	-280.3	-278.5
Focusing #3 I (A)	240.3	288.4	285.2	284.1	280.3	278.5
Matching #1 I (A)	254.1	290.6	260.9	213.5	170.6	81.3
Matching #2 I (A)	267.8	285.4	205.1	135.8	41.1	-51.9
End Coil #1 I (A)	257.0	251.4	268.1	257.0	245.7	235.9
Center Coil I (A)	258.9	258.9	258.9	233.1	207.0	181.2
End Coil #2 (A)	257.9	257.9	257.9	233.2	206.2	180.5

* The coils that shown are for positive x. I(-x) = - I(x).

Because the Italian coil design shown in Table 5 is somewhat more conservative than the design shown in Table 3, its temperature margin for the superconductor is a little higher. It is expected that the costs of the two coil sets will be similar within about 20 percent.

Quench protection of the Italian matching and detector magnet can not use quench back as the primary quench protection method for the magnet, because the winding bobbin is fabricated from stainless steel instead of aluminum. It is proposed that each circuit be protected by diodes and shunt resistors or that each coil or coil set have its own quench protection resistor. As with the other coil design, the coils in the matching and detector solenoid system will be closely coupled to the coils next to them. A quench of one coil will probably trigger a quench of all of the coils.

Some Concluding Comments

This report demonstrated that all of the MICE solenoid magnets could be built using MRI conductor in potted superconducting coils that can be cooled by conduction. Cooling for the coils can come from two-phase helium in tubes that are either attached directly to the coils or to the coil support structure. It has been demonstrated that there is adequate temperature margin in the superconductor to allow the MICE experiment to be operated over a range of average muon mementa and with various betas in the absorber that is located within the focusing coil pairs.

It appears that there are several ways to integrate the focusing coil with a liquid cryogen absorber or a solid absorber. Additional study is needed on the integration of the focusing coils with the absorber, so that the absorber can be changed with minimum disturbance on the focusing coils and the focusing coil cold-mass support system. The focusing coils must be designed in either the gradient mode with the two coils operating at opposite polarity or the solenoid mode where the two coils are operate at the same polarity. The focusing-coil cold inter-coil support-system must carry the inter-coil forces when the focusing coils operate in either mode.

The critical force issue with the magnets appears to be the location of the matching and detector coils set with respect to the focusing magnets at the ends of the cooling channel. Small changes in the spacing between the end focusing coils and the first matching coil appear to have a large effect on the longitudinal force seen by the cold mass support systems for both coil sets. Additional study is needed concerning the longitudinal forces through the cold mass supports for these coils.

It appears that the MICE solenoid magnet sets can be built by three different groups using three different superconductors. It appears that all three coil sets can use the same type of power supply. The integration of the magnets with one another is critical all through the design and fabrication process. For example, the coupling coil cryostat will be connected to the focusing coil cryostat through the vacuum vessel that houses the 201.25 MHz RF cavities. This vacuum vessel must be designed to carry the forces between coils. The interface between the focusing coil cryostat and the matching coil and detector coil cryostat must be carefully designed so that the interaction force between the two coil sets is carried by the interface between the two cryostats.

The design of the interfaces between coil sets must include the effects of iron and other material that may the experimental hall at the Rutherford Appleton Laboratory. The stray field of the MICE channel may preclude some operating scenarios. For example, the standard operating mode (Steps VI in Figure 2) has a zero net magnetic moment. Steps II, III, and V do not produce zero net magnetic moment. These steps will produce a larger stray field than the standard experiment (step V1). The standard mode with the focusing coils operating in the solenoid mode will also produce a large stray field. All of these design conditions may affect the design of the magnets and the detectors around the experiment. Interface design and integration of the magnets with the rest of MICE is critical

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